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**Barth, Torben C.; Timler Holm, Janus; Lindorff Larsen, Jakob**

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# A model for transfer baggage handling at airports

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Torben C. Barth<sup>1,2</sup> Janus Timler Holm<sup>2</sup> Jakob Lindorff Larsen<sup>2</sup>

<sup>1</sup>*Information and Telecommunication Services, Fraport AG*

<sup>2</sup>*Department of Management Engineering, Technical University of Denmark*

Contact: Torben C. Barth (tocb@dtu.dk)

## Abstract

This work deals with the handling of baggage from passengers changing aircraft at an airport. The transfer baggage problem is to assign the bags from each arriving aircraft to an infeed area into the airport infrastructure. The infrastructure will then distribute the bags to the handling facilities of the corresponding outbound flight. We present a static mixed integer model for the transfer baggage problem. The objective combines efficiency and quality criteria in a weighted linear function; minimizing the number of missed bags and transportation time, while ensuring a fair distribution of the workload and robustness. The model can be solved with a commercial MIP-solver. Furthermore, the use of the model in the dynamic environment during daily operations is introduced. The model includes two different approaches for increasing the robustness of the generated solutions. The uncertainty of the input data is studied and future approaches for improving robustness are discussed. The presented solution approach runs successfully as part of the operation control systems at Frankfurt Airport since 2008.

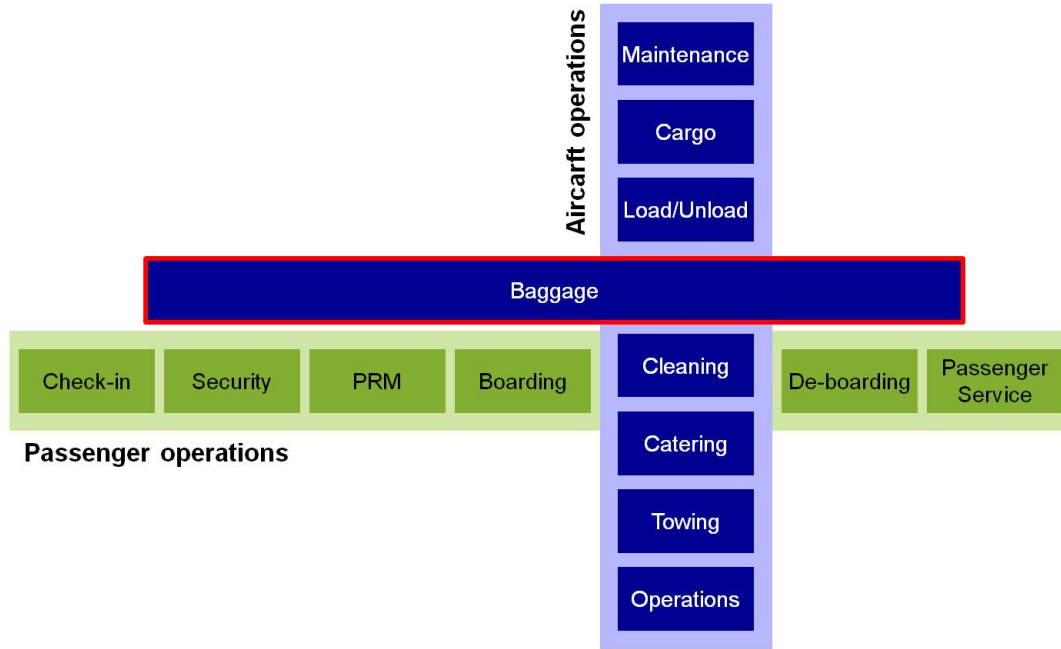
**Keywords:** *Airport baggage handling, Real-world optimization, Optimization under uncertainty, Robust optimization*

## 1 Introduction

Baggage handling is an important process during the ground time of an aircraft at an airport. It runs from the arrival until the departure of the aircraft and is a time critical bottleneck during airport operations. The airport operations during the ground time of an aircraft are shown in Figure 1. Baggage handling consists of many subtasks and can be distinguished in three main processes. The first process is the inbound baggage handling which is concerned with the handling of the bags from passengers arriving at the airport. The *transfer baggage* process deals with the handling of bags from passengers changing their aircraft at the airport. The outbound baggage handling combines the baggage flow from transfer passengers and the local check-in desks.

Especially the transfer baggage process is important for the success of large hub airports with many transfer passengers since the guaranteed connecting time for passengers and the corresponding luggage is a competition factor between hub airports. Baggage handling quality is mainly measured as a number of mishandled bags which is an important issue for customer satisfaction. Customer satisfaction combines the views from passengers and airlines. Furthermore, every missed connection can lead to compensations to the airlines and additional handling processes with the connected labor cost.

The transfer baggage process is essentially influenced by the choice of the infeed station in the airport infrastructure. The infeed stations are often grouped resources in handling halls in the basement of the terminal building, a group of infeed stations is referred to as *infeed area* in the following. At the infrastructure level the bags are then delivered via the baggage handling system



**Figure 1:** *Airport operations during aircraft ground time (on basis of Clausen [2010])*

(BHS) to the handling facilities of the outbound flights. The BHS consists at most airports of a connected conveyor belt network.

The complexity of the transfer baggage process depends on the airport layout and the available capacity. For example the handling capacities at the infeed stations are limited and not equally distributed over the airport. The location of the parking positions, infeed areas and handling facilities of the outbound flights define the structure of the problem.

In this article we study the operational transfer baggage process at Frankfurt Airport where more than half of the passengers are transfer passengers. In the considered setup, one dispatcher is responsible to control the transfer baggage process and to decide where the bags of the arriving aircraft are handled. In consequence, the dispatcher has to decide about several flights per minutes in peak times. The choice of the infeed area needs to be fixed before the arrival of the aircraft. Due to the high degree of uncertainty of the input data, e.g. position changes and delays, the decision should not be fixed before the final arrival of the aircraft. The whole situation and the best choices for all flights in a certain time interval can change within minutes. Therefore, the solutions need to be generated in near real-time during daily operations.

Experiences on the work on transfer baggage handling at Frankfurt Airport were already presented in the past by Barth and Franz [2008] and Barth [2012]. This report presents the underlying mathematical model in detail and shows important approaches to handle the uncertainty in the dynamic environment at airports. A similar approach was developed for Munich Airport by Kiermaier and Kolisch [2012]. Clausen and Pisinger [2010] developed a solution algorithm for the connected problem of handling critical transfer baggage. Furthermore, Clausen [2010] describes the airport ground handling process and presents the different problems in connection with airport ground handling.

Recently, we observe an increased amount of research in the connected fields of optimization of inbound baggage [Barth and Böckmann, 2012], [Barth, 2013], [Delonge, 2012], [Frey et al., 2012] and outbound baggage [Abdelghany et al., 2006], [Ascó et al., 2011], [Ascó et al., 2011], [Barth and Pisinger, 2012], [Frey et al., 2010], [Frey and Kolisch, 2010], [Frey and Kolisch, 2012].

Barth et al. [2013] presented a general scheduling framework for the different baggage handling problems at airports. The aim of the framework is to find a solution which combines the different

problems and provides the best overall solution in terms of efficiency and quality.

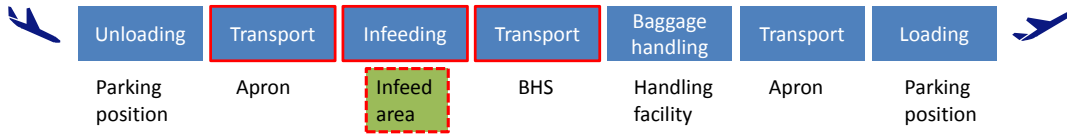
Böckmann et al. [2012] and Hounsgaard and Justesen [2012] presented lessons learned during the development and introduction of optimization solutions for baggage handling problems at airports. These works show the importance to respect the different real-world requirements in the developed solutions.

The purpose of this report is to introduce a general model for the control of transfer baggage handling in daily operations. Furthermore, the report aims to study the uncertainty in a data analysis. The model includes different approaches to increase robustness of the solutions. For evaluating the need of increasing the robustness, the input data and the underlying uncertainty is studied at the example of position changes and time updates. Finally, an improved solution method based on the data analysis is sketched.

The further outline of this report is as follows: At first in Section 2 the problem of transfer baggage handling is introduced in more detail. Afterwards, important steps of the solution process are presented in Section 3. Section 4 describes the mathematical model for the transfer baggage problem. In Section 6 the use of the model in the dynamic environment at an airport is explained. Furthermore, the uncertainty of the data and the modeling of the robustness are studied. Section 5 shows important results of the use of the model at Frankfurt Airport. Finally, Section 7 presents an outlook of future research based on the presented model.

## 2 Problem description

The transfer baggage handling process is shown with its different activities in Figure 2.



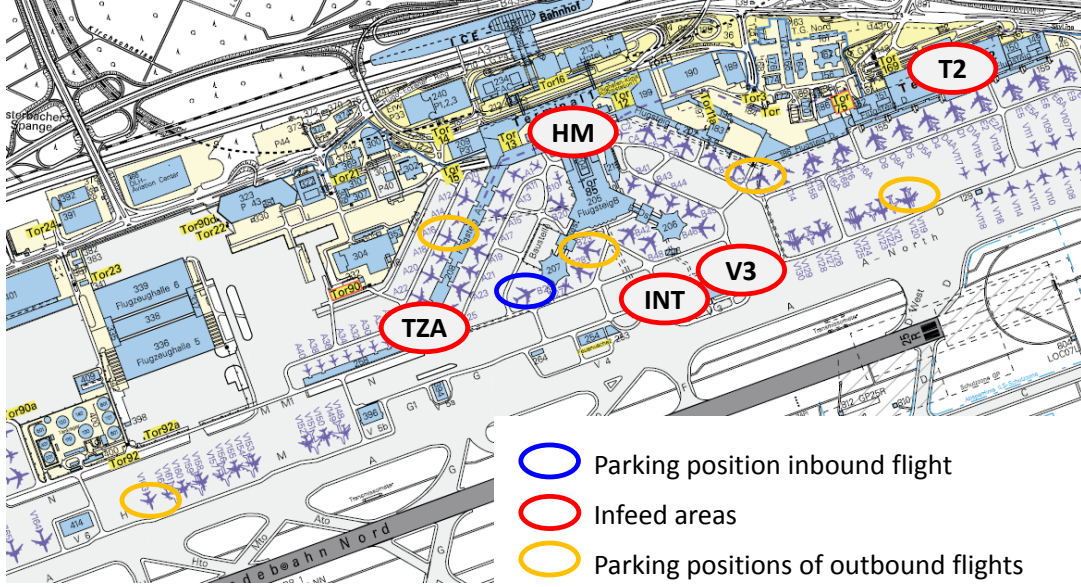
**Figure 2:** Process chain of the transfer baggage handling at an airport. The red marked activities are influenced by the choice of the infeed area.

After the arrival of the aircraft at the parking position, the unloading of the bags from the aircraft starts. In the next step the bags are transported with vehicles to the infeed area and the connected infeed stations at the airport infrastructure. At the infeed stations the bagtags are scanned and the destination of each bag is determined. Depending of the status of the flight the bags are X-rayed to fulfill the security regulations. The bags are then transported via the BHS to the handling facilities of the outbound flights. At the handling facilities of the outbound flights the bags are loaded to containers or dollies. Afterwards, the bags are transported to the parking position of the departure aircraft. Finally, the bags are loaded to the aircraft. The process of loading the last bags to the aircraft has to be finished shortly before the expected departure time.

At Frankfurt Airport normally two containers or dollies, containing transfer or inbound baggage, are paired together after the unloading. The transportation of paired containers or dollies is called *trip* in the following. For each trip an assignment to an infeed area has to be chosen. This assignment has a huge impact on the process time for each of the bags in the containers, and therefore determines whether or not the individual bags will arrive at the transfer flight in time.

For each trip it is necessary to choose the best infeed area. The decision of the specific infeed station in the infeed area will be made dynamically during the operations by the drivers of the vehicles. The choice of the infeed station has a negligible impact on the overall process time. For every connecting bag the process time depends on the position of the arriving aircraft, the selected infeed area and the handling facility from the outbound flight. Since each connection has another available time period for the connection process, it is important to find a good assignment of the

different trips to the handling facilities in such a way that as many bags as possible hold their connection. Figure 3 shows the location of handling facilities at Frankfurt Airport. Furthermore, it illustrates an example for an arriving aircraft with the corresponding connecting flights.



**Figure 3:** Example of an arriving aircraft with corresponding connecting flights and the possible infeed areas

The infeed areas have limited capacities in respect to the number of handled bags per time interval. The choice of infeed areas can be limited for certain trips in dependency of properties of the trips e.g. limits on container sizes. For some flights it is not allowed to select more than one infeed area for the different trips of the flight. Additionally, there can exist restrictions between consecutive trips of one flight. An important point is that the bags are handled in a first-in-first-out strategy. In practical terms, this means that it is not possible to prioritize critical trips or bags if the capacity limit is exceeded at an infeed area. The following criteria were determined as most important for the objective:

- Minimize the number of missed connections
- Minimize transportation time from the aircraft to infeed area at the apron
- Maximize capacity buffer for unforeseen events at the infeed areas
- Balance the use of the infeed areas
- Minimize transportation time from infeed area to handling facility of the outbound flight in the BHS

The three minimization criteria can be computed for each assignment. The other two criteria depend on the combination of assignments from the trips to the infeed areas. Since the capacity depends on the combination of the handling of the different flights, it is necessary to develop an optimization model including all flights expected within the next hours. The calculation of the number of missed bags demands to respect the whole process chain for every single bag in a trip. Summarized the choice of the infeed area has an impact on the following processes (marked with red boxes in Figure 2):

- Transport time from the aircraft to the infeed area. If an area close to the parking position of the aircraft is chosen, the distance and hence transport time is short.
- Waiting time at infeed area. If the infeed area is already working at the capacity limit, the bags must wait before they can be loaded into the BHS.
- Handling time at infeed area. The capacity or handling speed at each infeed area varies due to the preallocated heterogeneous resources. This influences the handling time of the bags.
- Transport time from infeed area to outbound handling facility. When the bags travel through the BHS, the transport time varies depending on distance from infeed area to handling facility of the connection flight.

The handling facility of the outbound flight is chosen one to several hours before the departure of the aircraft. Therefore the handling facility is a fixed input value for the selection of the infeed area. The parking position of the outbound flight is defined by the flight schedule. In consequence the transport and handling times for these steps are considered as given constants.

For each individual bag the transfer time is calculated, depending on the estimated on-block time (EON)<sup>1</sup> of the inbound flight and the estimated off-block time of the outbound flight. If the transfer time does not exceed the available time, the baggage is in time and the transfer went successfully. Otherwise the bag is categorized as missed and may result in a loss of goodwill or a compensation to the airline.

The problem is to assign each trip containing transfer baggage to one of the available infeed areas. The considered objective is to use the existing capacity to optimize the different objective criteria including the number of missed connections. This problem is called the *Transfer Baggage Problem*, later referred to as TBP.

### 3 Solution process

In this section the developed solution process is described. For solving the mathematical model which is introduced in Section 4 the data of the flights need to be prepared. The most important steps are to determine the trips and the possible assignments from a trip to the infeed areas.

#### 3.1 Trips

Trips are generated for each considered inbound flight, consisting of 1-2 transfer baggage containers or dollies. For simplification we use only the term “container” in the following. The handling process of bags from bulk compartments which are loaded loose in the aircraft, are identical after the loading in the dollies. Each trip holds information about the following:

- Parking position of the inbound flight.
- Start time of trip, when the unloading of the containers is done.
- Containers in trips, also holding information about the baggage in each of the containers.

Each inbound flight holds information about the containers in the flight, as well as the information about how long time it will take before each of the containers is unloaded. The grouping of the containers to trips is done according to predefined given rules depending on the aircraft type. It is important to note that the grouping of more than two containers in one trip does not change the logic of the solution process. It can happen that inbound and transfer containers are included in one trip. In this case it depends on the procedures at the airport in which order the containers will be delivered at the infrastructure. The changed process time needs to be respected in the calculation of the process times. Furthermore, the transportation time between the different

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<sup>1</sup>The status *on-block* is defined as official/real arrival at the parking position and *off-blocks* as official/real departure from parking position

destinations should be respected in the objective since ideally the chosen infeed area should be close to the inbound handling facilities.

Depending on the available load data of the transfer flights the bags per container can be identified. In most cases only overall connecting information for the bags in a flight are known. In these cases the contained bags need to be estimated and the further calculation will be based on average values of the possible bags in the container.

### 3.2 Assignments

Multiple possible assignments are generated for each trip, one for each feasible infeed area. The generation of the assignments considers the opening hours of the infeed areas. Additionally, the given hard restrictions on infeed areas and specific flights or container types are respected.

For each of the generated assignments, values determining the quality of the assignment need to be calculated. These values will be used for determining the objective criteria of the model and are defined as following:

$u_a^{BHS}$  This parameter holds the total travel time through the BHS, summed together for each bag in the assignment  $a$ . The value is easily calculated by going through all bags in the assignment, and extracting the distance from the infeed area to handling facilities of the connecting flights.

$u_a^{crit}$  This parameter is a sum of a value given to each bag in the assignment, based on the buffer time. The buffer time gives information of the criticality of each bag. Small buffer times are much more likely to miss the connection than a connection with a large buffer time. For a given bag the buffer time can be determined by first calculating the total processing time used to transfer the bag from the inbound flight via the infeed area of the assignment to the outbound flight. This is the sum of times used in the process chain seen in Figure 2. This processing time is subtracted by the available connecting time gives the buffer time.

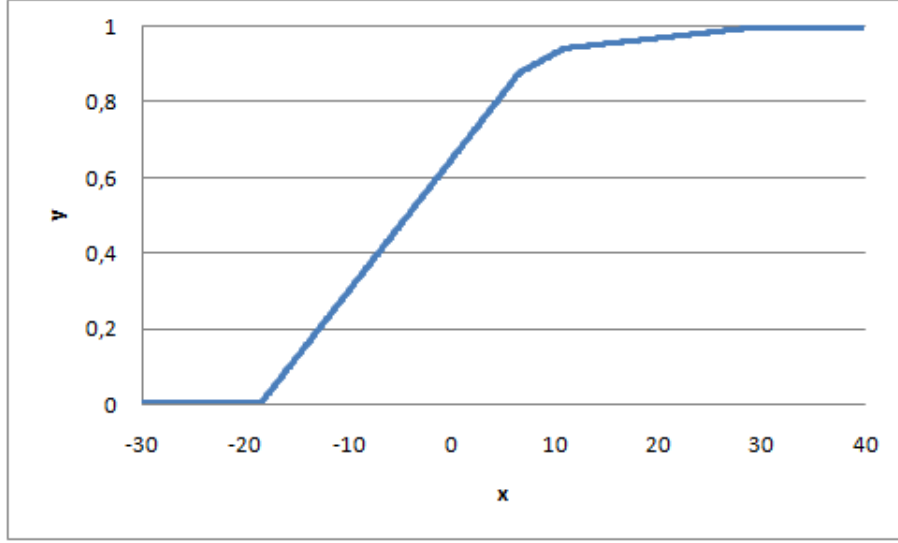
Based on the buffer time, the connecting probability can be calculated. A large buffer time is preferable and thus gives a higher (better) probability. However the increase in the probability gets lower and lower when the amount of buffer time increases. This means buffer time gets less valuable for higher buffer times. For each bag this is calculated from the piecewise linear function given by Equations (1)-(2). An overview of how the connecting probability function behaves, can be seen in Figure 4. As seen in the equations and in the figure, a connecting probability will always be between 0 and 1. Additionally, this value can be adjusted based on the number of alternative connections to the same destination, where an uncommon destination is more critical to miss than a common one. The connecting probability of the single bags are then summed together to define the value of the assignment.

$$y = \begin{cases} 0.003x + 0.91 & x > 10.8 \\ 0.015x + 0.78 & 6.5 \leq x \leq 10.8 \\ 0.035x + 0.65 & x < 6.5 \end{cases} \quad (1)$$

$$y = \min(1, \max(y, 0)) \quad (2)$$

$u_a^{apron}$  This parameter is the transportation time on the apron from the parking position of the inbound flight to the infeed area. The value can easily be extracted from a given time distance matrix. An infeed area close to the parking position, will result in smaller driving times, thus giving a better value for the assignment, since transportation time is minimized.

$u_a^{missed}$  This parameter counts the number of missed connections. For each bag in the assignment, the buffer time is checked, and if the bag has a negative buffer time, the number of missed connections is incremented by a scaled factor depending on the number of alternatives flights during the day or the next week.



**Figure 4:** *Single bag connecting probability ( $y$ ) dependency on buffer time ( $x$ )*

## 4 Model

In this section the general model for the TBP is presented. The model relies on time discretization and has a limited time horizon. Only aircraft arriving within this time horizon are considered in the optimization.

The model includes the capacity restrictions at the infeed areas. Since the exact available capacity is hard to determine and the exact arrival times cannot be predicted a strict limit does not express reality appropriately. The idea is to avoid a high capacity use, to leave a buffer for unforeseen events e.g. break down of infeed stations or unexpected arriving bags. Furthermore, full capacity use over longer periods should be avoided to prevent break downs.

The capacity is captured with the following steps:

- Desired maximum capacity use,  $C_{i,t}^{des}$ . A capacity no higher than this level is desired at infeed area  $i$  at time slot  $t$ .
- Technical capacity,  $C_{i,t}^{tech}$ . The average capacity limit defined by the technical limitations of the infeed stations and the given level of manpower.
- Overcapacity step 1,  $C_{i,t}^{queue1}$ . Overcapacity up to this level is slightly penalized as queuing baggage. The undhandled bags will use capacity in the subsequent time period and

**Table 1:** *List of indices and sets*

INDEX	SET	DESCRIPTION
$a$	$A$	feasible assignments of trips from inbound aircraft to infeed areas
$b, bb$	$B$	trips
$i$	$I$	infeed areas
$a$	$A_b$	subset of feasible assignments for a specific trip $b$
$a$	$A_i$	subset of feasible assignments for a specific infeed area $i$
$f$	$F$	set of all considered flights
$a$	$A_f$	all feasible assignments of flight $f$
$t$	$T$	time-steps, dividing the time horizon



**Table 2:** *List of parameters*

PARAMETER	DESCRIPTION
$u_{a,t}$	amount of resource used in time slot $t$ of assignment $a$
$u_a^{missed}$	number of missed connections for assignment $a$
$u_a^{crit}$	total buffer of all bags in assignment $a$
$u_a^{apron}$	transport time from the parking position to the infeed area for assignment $a$
$u_a^{BHS}$	total transport time from the infeed area to the handling facility of all bags in assignment $a$
$C_i^{des}$	desired maximum capacity at infeed area $i$
$C_i^{tech}$	technical capacity at infeed area $i$
$C_i^{queue1}$	workload limit of extended capacity at infeed area $i$ .
$C_i^{queue2}$	workload limit of additionally extended capacity at infeed area $i$ .
$w^{missed}$	weight of cost term for missed connections
$w^{crit}$	weight of cost term for the buffer time
$w^{apron}$	weight of cost term for apron transportation
$w^{BHS}$	weight of cost term for transportation in the BHS
$w^{des}$	weight of capacity use above the desired capacity use
$w^{queue1}$	weight of cost term for bags in queue1
$w^{queue2s}$	weight of cost term for bags in queue2
$w^{penalty}$	weight of cost term for bags above
$w^{balance}$	weight of cost term for balancing workload between infeed areas

**Table 3:** *List of variables*

VARIABLE AND DOMAINS	DESCRIPTION
$x_a \in \{0, 1\}$	indicates if assignment $a$ is selected
$y_{i,t}^{des} \in \mathbb{R}_+$	use of capacity exceeding the desired capacity use $C_i^{des}$ at infeed area $i$ in time-step $t$
$y_{i,t}^{queue1} \in \mathbb{R}_+$	workload stretched above technical capacity by up to $C_i^{step1}$ at infeed area $i$ in time-step $t$
$y_{i,t}^{queue2} \in \mathbb{R}_+$	workload stretched above technical capacity between $C_i^{step1}$ and $C_i^{step2}$ at infeed area $i$ in time-step $t$
$y_{i,t}^{penalty} \in \mathbb{R}_+$	ensures feasibility even if workload is exceeds $C_i^{step2}$ at infeed area $i$ in time-step $t$
$q^{avg} \in \mathbb{R}_+$	average load of all infeed areas
$q_i^{plus} \in \mathbb{R}_+$	positive deviation from mean load at infeed area $i$
$q_i^{minus} \in \mathbb{R}_+$	negative deviation from mean load at infeed area $i$
$q^{max} \in \mathbb{R}_+$	maximum load of infeed areas
$q^{min} \in \mathbb{R}_+$	minimum load of infeed areas
$q \in \mathbb{R}_+$	total deviation from mean load at infeed areas

complicates handling through additional sorting effort.

- Overcapacity step 2,  $C_{i,t}^{queue2}$ . Overcapacity exceeding step 1 and up to this level is additionally penalized as queuing baggage and will also use capacity in the subsequent time period. This overcapacity use should be avoided and only be used in periods with peak demands.

Based on these levels the model is allowed to queue up a certain amount of bags at an infeed area. However this queue has a negative influence on the capacity in the subsequent time period. This reflects the physical situation in reality where extraordinary many bags may be served as a result of extra hard working crew and/or queuing baggage. The queued bags will be handled in the next time period and reduce the capacity accordingly. The advantage of this formulation is that it reflects a certain amount of flexibility in the capacity and encourages the model to maintain buffer capacity.

The model seeks to optimize multiple criteria simultaneously. This is minimizing transportation time, time spend on conveyor belts, queuing baggage and missed connections while maximize the buffer time and balanced use of infeed area. The different objectives are combined by the weighted sum of the criteria, as seen in the objective function (3). Though, this allows optimizing on many criteria simultaneously it also gives rise to the challenge of balancing the criteria against each other across different units.

In the model description below we use the symbols given in Tables 1 - 3.

$$\begin{aligned} \min \quad & \sum_{a \in A} (w^{missed} u_a^{missed} + w^{crit} u_a^{crit} + w^{apron} u_a^{apron} + w^{BHS} u_a^{BHS}) x_a \\ & + \sum_{i \in I, t \in T} w^{des} y_{i,t}^{des} + w^{queue1} y_{i,t}^{queue1} + w^{queue2} y_{i,t}^{queue2} + w^{penalty} y_{i,t}^{penalty} \\ & + w^{balance} q \end{aligned} \quad (3)$$

$$s.t. \quad \sum_{a \in A_b} x_a = 1 \quad \forall b \in B \quad (4)$$

$$\sum_{a \in A} x_a u_{a,t} + y_{i,t-1}^{queue1} + y_{i,t-1}^{queue2} + y_{i,t-1}^{penalty} \quad \forall t \in T, i \in I \quad (5)$$

$$\leq C_i^{des} + y_{i,t}^{buffer} + y_{i,t}^{queue1} + y_{i,t}^{queue2} + y_{i,t}^{penalty} \quad \forall t \in T, i \in I \quad (6)$$

$$C_i^{des} + y_{i,t}^{des} \leq C_i^{tech} \quad \forall t \in T, i \in I \quad (7)$$

$$C_i^{tech} + y_{i,t}^{queue1} \leq C_i^{step1} \quad \forall t \in T, i \in I \quad (8)$$

$$C_i^{step1} + y_{i,t}^{queue2} \leq C_i^{step2} \quad \forall t \in T, i \in I \quad (8)$$

Constraint (4) ensures that every trip is assigned to exactly one infeed area. Constraint (5) calculates the capacity use and makes sure that stretched workload is carried over to next time period. Constraint (6) ensures that use of buffer capacity is only possible between desired workload and technical workload capacity. Constraint (7) ensures that use of *queue1* capacity is only possible between technical workload and step 1 workload capacity. Constraint (8) ensures that use of *queue2* capacity is only possible between step 1 workload and step 2 workload capacity.

To optimize the balance between the infeed areas we add the following constraints to calculate the absolute deviation from the average capacity use.

$$q^{avg} = \frac{\sum_{a \in A, t \in T} u_{a,t} x_a}{\sum_{i \in I, t \in T} C_i^{tech}} \quad (9)$$

$$q^{avg} + q_i^{plus} - q_i^{minus} = \frac{\sum_{a \in A, t \in T} u_{a,t} x_a}{\sum_{t \in T} C_i^{tech}} \quad \forall i \in I \quad (10)$$

$$q = \sum_{i \in I} (q_i^{plus} + q_i^{minus}) \quad (11)$$

Constraint (9) calculates the average utilization of all infeed areas. Constraint (10) defines the deviation from the mean utilization for all infeed areas. Constraint (11) calculates total absolute deviation from the mean utilization.

Alternatively, the balance can be modeled as the distance between the maximum and the minimum utilization on any infeed area. This can be formulated with the following constraints.

$$q^{max} \geq \frac{\sum_{a \in A_i, t \in T} u_{a,t} x_a}{\sum_{i \in I, t \in T} C_i^{tech}} \quad \forall i \in I \quad (12)$$

$$q^{min} \leq \frac{\sum_{a \in A_i, t \in T} u_{a,t} x_a}{\sum_{i \in I, t \in T} C_i^{tech}} \quad \forall i \in I \quad (13)$$

$$q = q^{max} - q^{min} \quad (14)$$

Constraint (12) calculates the maximum utilization of all infeed areas. Constraint (13) calculates the minimum utilization of all infeed areas. Constraint (14) calculates the difference between the maximum and the minimum utilization.

## 4.1 Extensions

This section describes different extensions which can be used for different settings or situations at airports. These extensions make the model more flexible since it is possible to adjust it to the requirements of a specific airport.

**Single trip constraint** Constraint (15) is defined for each trip with only one transfer container. These trips can only be handled at an infeed area, where at least one of their neighbouring trips is handled. The rationale behind this constraint is that a change in the unloading order should not cause mishandling. In reality these single container trips, might be combined with one of their neighbouring trips, thus transporting three containers at once.

$$\sum_{a \in A_i \cap A_{bb}} x_a \leq \sum_{b \in N_{bb}, a \in A_i \cap A_b} x_a \quad \forall i \in I, bb \in B^{single} \quad (15)$$

The set  $B^{single}$  contains all trips with only one transfer baggage container.  $N_{bb}$  is set of all neighboring trips of the trip  $bb$ . Constraint (15) enforces that an assignment of a trip with a single trip can only be at an infeed area where at least one of the neighboring trip is handled.

**Limit of different infeed areas per flight** For some flights there exist limitations on the number of different infeed areas. For example only one vehicle could serve bulk flights. A limitation of the number of different infeed areas can be modelled in the following way:

$$x_a \leq z_{f,i} \quad \forall f \in F^{limit}, i \in I, \forall a \in A_i \cap A_f \quad (16)$$

$$\sum_{i \in I} z_{f,i} \leq 1 \quad \forall f \in F^{limit} \quad (17)$$

The left side of Constraint (17) can be adjusted to the needs of the specific airport or even in dependency of the different flights. In the presented example all trips of the defined flight will get the same infeed area.  $F^{limit}$  denotes all flights with a limitation of the number of infeed areas. The variable  $z_{f,i} \in \mathbb{R}_+$  can only be zero if the infeed area  $i$  is not used by any assignment of flight  $f$ .

**X-ray capacity** Security regulations sometimes require that bags from predefined origins need to be X-rayed before being inserting into the BHS. This can lead to additional capacity limitations for given bags needing an X-ray, which is typically below the general capacity. Depending on the setup at the airport not all infeed stations can be used for bags which need an X-ray process. The model can be extended by additional capacity constraints according to the existing capacity constraints. The difference is that the capacity limits are set to the available capacity for X-ray bags. The capacity use will be determined based on  $u_{a,t}^X$  which counts the number of bags which need to be X-rayed at time  $t$  for assignment  $a$ .

**Hard constraints** All hard constraints limiting the choice of infeed areas for specific flights can either be incorporated during assignment generation – by not generating these assignments – or with an extra constraint forbidding the choices by setting  $x_a = 0$  in these cases. Hard constraint can reflect either the law or agreements made with the different airlines.

**Minimize number of infeed areas per flight** Since the actual loading order can deviate from the expected, changes in the arrival order of the containers can occur. The changes can have consequences on the pairing of trips especially if there exist trips with only one transfer container. In these cases it can help that all trips in a flight are assigned to the same infeed area. Furthermore, handling procedures are not always followed during transportation or unloading. It has shown that handling errors and process problem less often occur if the same or only two different infeed areas are chosen per flight. Therefore it can make sense to minimize the number of different infeed areas. This is modeled as a soft constraint, by adding the sum of the counting variables from Constraint (16) to the objective function, as an additional criterion.

**Balanced capacity for flexible time periods** The calculation of the balanced capacity use can also be based on time slots. The variable  $q_t$  then measures the balance at the time slot  $t$ . In the objective it is then summarized over all time slots. Furthermore, the time slots can be defined in different sizes to seek for a balanced use for example in 15 minute time periods.

## 5 Results

The number of variables and terms in the objective is bounded by  $O(|A| + |T| \cdot |I|)$ . Since the number of assignments depends on the number of trips (it is easy to see that the number of trips depends on the number of flights) and the number of available handling facilities, we get the bound  $O(|I| \cdot (|F| + |T|))$ . The bound for the number of constraints is as well given by  $O(|I| \cdot (|F| + |T|))$ .

The model has been used at Frankfurt Airport since 2008. The most important success factors are listed in this section. One issue was to generate easy human readable information about the solution to show the direct cost and how the soft constraints are calculated. Time stamps from operations are included in the dynamic calculations for increasing data quality of the flights currently in planning. It showed that the decisions should be made close to the arrival time of the flights to reach a high decision quality.

At Frankfurt Airport only one dispatcher is responsible for the process. Before the start of the project he was at the limit of the workload he could manage. Today, still one dispatcher is responsible for the process although the number of flights has substantially increased since then. Furthermore, the quality of transfer baggage process has increased in the last years as was reported by both Fraport and Lufthansa<sup>2</sup>.

The model helped making differences between lived dispatch strategy and the management's dispatch philosophy visible. Decisions can now be measured and it is easy to show numerically what the difference between two different choices is. Furthermore, it helped aligning the strategy over all dispatcher since they are now all supported by the same suggestions. The dispatcher follows in average about 80% of the suggestions and the decision support is well accepted. Higher

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<sup>2</sup>The largest airline at Frankfurt Airport

acceptance rates are possible but the dispatchers are encouraged to still be an active part of the decision process to be prepared for disruptions and system break downs. Numerically studies have shown that the overall objective can be improved by 10% if all decisions would be chosen according to optimization model. The improvement is on one hand based on a better balancing of the different criteria and on the other hand a better utilization of the infeed areas.

The model produces additional information which are used in the transfer baggage process. For example the expected process times is included as an additional information in the dispatch system. Another example is that critical flights are identified and published. This information is used in bottleneck situation to use the scarce resources for critical flights.

Our experiences showed that the model can be used in a real-world context and helps increasing robustness of the generated schedules.

## 6 Data analysis

To deal with the TBP in daily operations, Frankfurt Airport is currently using the presented model which is solvable within seconds by a commercial solver. The model relies only on the current available data and it assumes that this data is reliable. But as landing times, transport times, handling times etc. are subject to uncertainty, this assumption is clearly wrong.

To improve the understanding of the environment in which the model operates, a detailed analysis is presented in the following. Frankfurt Airport provided data covering a month of operations. The data is grouped in two categories; where the first are updates on estimated on-block times (EON), with 163 150 observations distributed over 18 387 distinct flights. EON is the expected time of arrival of the aircraft at the parking position where its tires are blocked to prevent it from moving, hence “on-block”. The other category are position changes happening at most two hours before on-block for inbound flights, with 10 361 observations distributed over 5 458 flights. In the following these categories are studied separately.

### 6.1 Updates on estimated arrival time

Each update holds information about: the time when the update is reported (*ReportTime*) and the new EON and the actual on-block time (ONB). Using this the time before ONB the update is given is calculated, as well as the difference in the estimated and actual on-block:

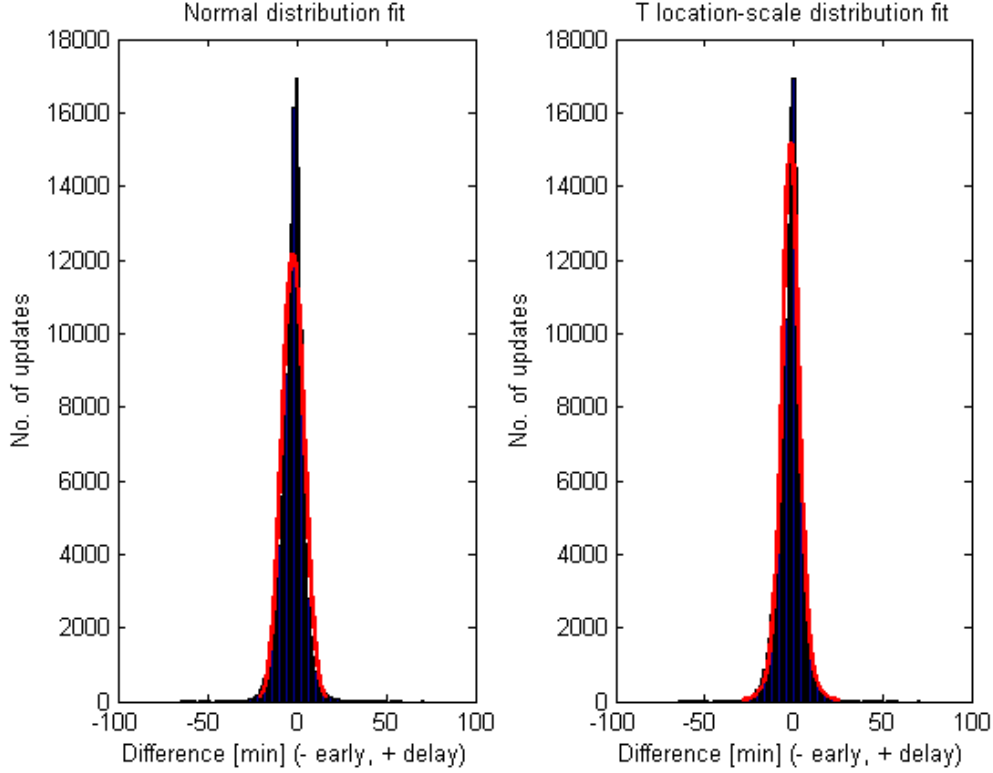
$$TimeBefore = EON_{new} - ReportTime$$

$$Difference = ONB - EON_{new}$$

The accuracy of the updates are investigated by plotting a histogram of the differences. This is done in Figure 5. Assuming the delay on arrival times of the flights are following a normal distribution [Mueller and Chatterji, 2002], a fit has been added to the histogram. Furthermore a T location-scale (TLS) distribution has been fitted to account for an even better representation of the data. TLS is based on the normal distribution but transformed by a third parameter  $\nu$ . This distribution approaches the normal distribution when  $\nu \rightarrow \infty$ .

This results in the normal distribution:  $Difference \sim \mathcal{N}(-2.0215, 6.0661)$  and TLS distribution parameters of:  $\mu = -1.739$   $\sigma = 4.062$   $\nu = 4.552$ .

The normal distribution makes a decent fit, but it can be seen that both the peak and tails of the histogram are larger than the ones in the normal distribution fit. The TLS distribution fits well and definitely has a better representation of the tails and peaks. It can be seen that the EONs are not fully symmetrically as both fits assume, which could explain the differences between the fits and the histogram. But all in all it is concluded that the TLS distribution can be used to describe the quality of the EONs.



**Figure 5:** *Histogram of difference for all updates and fitted normal distribution*

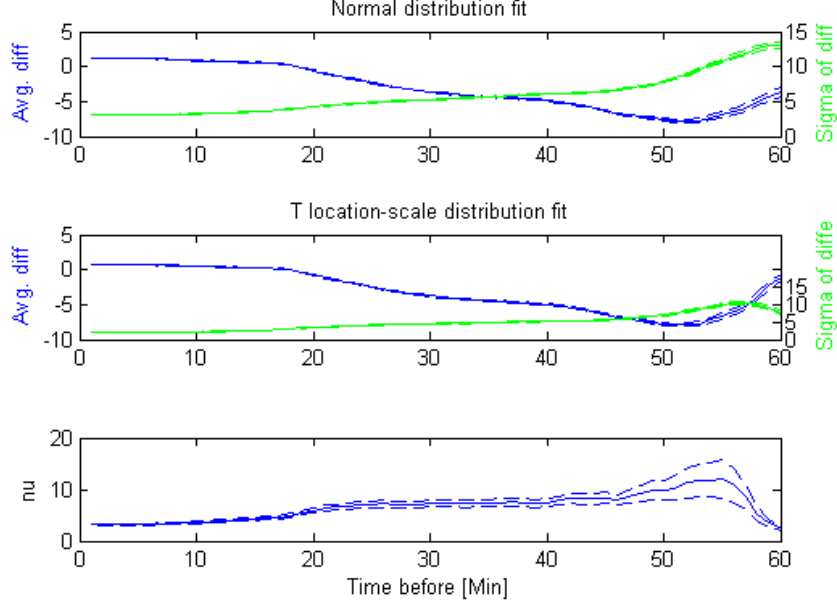
**Time dependent** The results from the previous section assume that all flights report EON update constantly, but in reality this only happen about 9 times on average during the last 2 hours before arrival. The consequence is that, for the airport, available EONs will be old to some extent. In this analysis we will therefore look at the latest update for all distinct flights, and disregard the rest of the updates. If no update is available the flight is not considered. It can be shown that these latest updates to various time points also fit the two distributions in a similar way as all the updates did.

For the EONs available at each minute we approximate a fit of both distributions. This results in Figure 6 where the changes in the distributions can be seen over time. This figure also shows a 95% confidence interval on the parameters defining the distribution fit. These graphs should be compared to Figure 7 showing the average age of the updates and the numbers of distinct flights as a function of time.

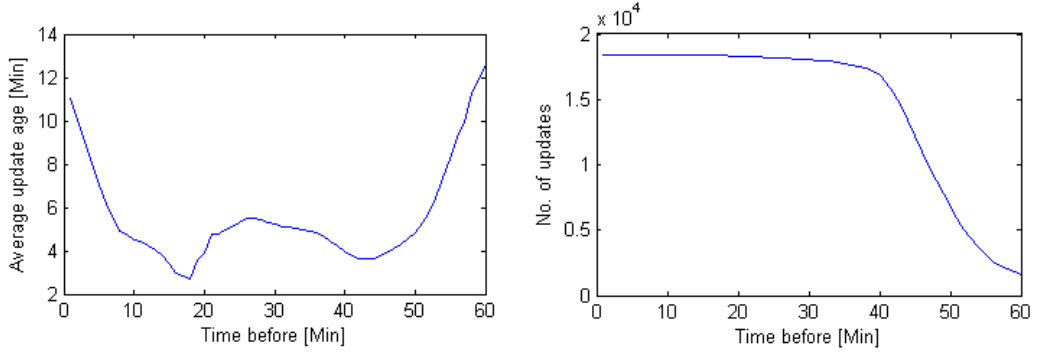
Both distributions follow the same tendency up to about 50 minutes before actual ONB. The variance is steadily increasing whereas the mean is steadily decreasing. The decrease in the mean shows that earlier estimates are predicting a later arrival than the actual one. While the updates close to on-block ends up prediction a later arrival than the actual. The increasing variance is also aligned with the general assumption that earlier updates should be less precise. The parameter  $\nu$  is increasing until 55 minutes indicating that the T location scale distribution approaches a normal distribution.

After 55 minutes we see an increase in the mean and the variance is flattening off. The sudden change in tendency coincides with the sudden fall in the number of distinct flights between 40 and 60 minutes. At 60 minutes less than one-tenth of the flights remain. This results in a lower quality of the result shown by the confidence interval. Another consequence is that the much fewer flights reporting EONs updates earlier than one hour before, may lead to a biased result. The remaining flights may only represent long distance flights or flights of extraordinary importance. Therefore

these results should be used with caution.



**Figure 6:** *Distributions and 95% confidence interval over time*



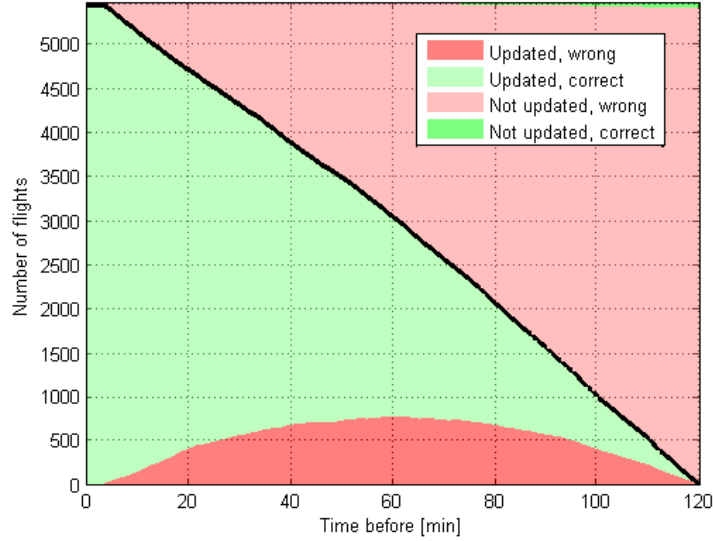
**Figure 7:** *Update age and number of updates*

## 6.2 Position changes

This analysis is based on a dataset containing the position changes. Some flights have multiple, some only have a single, while some are not even listed in the dataset. This analysis will focus only on the flights that do.

Each position change is listed with a time stamp, which can be used to tell, how long before on-block the change occurs, as well as the new position, the old position and the final position. Here positions equal to the final position are interpreted as correct, while other positions are interpreted as wrong. Thus a position change can either result in a position being changed from a wrong position to the correct position, from a correct position to a wrong position or from a wrong position to a wrong position.

Using this it can be seen how many flights have the correct position, at a given time before on-block, this is plotted in Figure 8. In the figure a solid black line, divides the flights which not yet have received a position change in the upper right, with the flights having received a position change in the lower left. While the red areas define the flights with a wrong position, either given by position before first update, or by position after an update. The green areas define the flights with the correct position, either given by position before first update or by position after an update.



**Figure 8:** *Flights with position changes*

When a flight receives its first position update, it is moved from the upper right triangle to the lower left triangle. Here it is included in either the green or the red area, depending on the outcome of the position change; either new position is correct or it is wrong. Either way it might receive another position update at a later time, shifting it from green to red or opposite.

There are 18 387 flights in current month and only 5 458 are getting a position update, which tells that over two thirds of the flights are reliable, since they do not occur in the dataset for position changes. For these flights it is assumed that they are assigned a position more than two hours before on-block, and keeps the given position for the whole duration of the flight. Thus all the positions of these flights are at the correct positions. Figure 8 shows the amount of flights assigned to a wrong position at a given time before on-block, as the sum of the red areas. This sum divided by the total 18 387 flights gives the probability of a flights position being wrong, this is plotted in Figure 9 along with a 95% confidence interval on the probability.

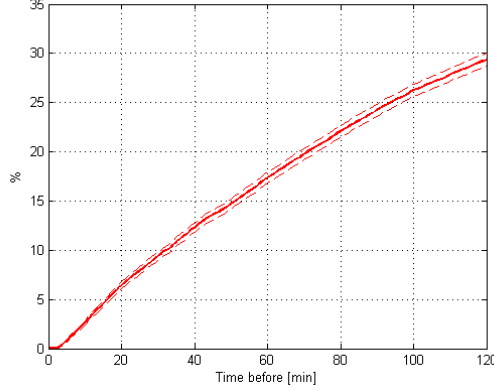
Looking at the figure it can be seen that the probability of a position being different to the final position decreases almost linearly from almost 30% two hours before on-block till 0% at about five minutes before on-block. This information can be used as a way to tell an optimization how much the positions should be trusted.

This analysis shows that relevant patterns can be extracted from the existing date. These patterns form a potential for a more advanced modeling and simulation. Further studies can group the data by various criteria, such as aircraft type, to extract even more detailed results.

### 6.3 Robustness

We define robustness as the ability of the schedule to cope with changes of the input data after decision is taken. The robustness in the basic model is enhanced by including two kinds of buffer. On the one hand we measure for each single bag the connecting time and calculate if there is some





**Figure 9:** *Probability position not being final*

buffer in the connection time. Each minute of saved process time gives a bonus in the objective function. If the buffer is small a minute counts more than in situations with larger buffer times. After a certain border a reduction of the process time is not measured because we assume that these connections are safe. One remarkable point of the model is that also connections with negative buffer times are considered. A shorter process time can help holding the connection in the event that the departure flight is delayed. On the other hand capacity is reserved at the handling facilities for critical flights or unforeseen events. This means in practical terms, that a high capacity use is penalized. The weights of the different objective terms ensure that this high capacity use is only allowed if a flight has critical connections.

## 7 Future work

Further work on the model can be done to improve quality of the produced results. The uncertainties related to the problem are an important part of the setup in which the model operates. So far the uncertainties are handled by rewarding capacity buffer as well as buffer in the connection time, for the individual bags. This enables solution applicability in the real life despite the fact that the model is far more simplified than the real world. In this process the information lying hidden in the uncertainties is lost. The data analysis shows that the uncertainties contain much information which can be useful for the model and therefore can lead to better solutions. Today, a lot of additional data describing most of the different uncertainties already exist, because many operations in the airport are monitored electronically and stored in databases. A more throughout analysis of this data can be done to improve the model or develop alternative solution methods.

By incorporating the uncertainties, there is a potential for improving the solution to reflect reality in a more appropriate way. A straightforward way of doing this is to change the model into a simple stochastic model. The scenarios can be developed from the already analyzed data. The downside with stochastic models is that solving it will be more time-consuming. This can take too long since the results are needed quickly during the operations and data can even change during the calculation.

A more complex way of incorporating the uncertainties is to follow the idea of a model enhancement approach like the one described by De Bruecker et al. [2013]. In this work an related problem in airport operations is solved using a combination of a MIP model and simulations. By alternating between evaluating the model and the simulation, the model is iteratively improved based on the feedback from the simulations. In this approach, the information in the uncertainties are affecting the model though the simulation without significantly increasing the complexity of the model. The presented data analysis and further work in analyzing the uncertainties can be the foundation of the simulation. For the beginning, the simulation can be used to adjust the

value of the buffers to ensure that the model adds buffers where it is effective and needed while it can refrain from using it when it is unnecessary. Despite that this method looks promising, it will prolong the running time of the model. The model needs to be executed multiple times, with simulations in between. The challenge will be to keep the time consumption on an acceptable level.

In the future the model may also be able to handle the order in which the baggage is handled at the infeed stations. Here the model enhancement can further help identifying critical trips and to decide if they should be handled before uncritical trips. One has to keep in mind that this can demand a change of business processes but simulation can assess the value of such a change.

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